Refractive Index, Viscosity, Density, and Speed of Sound of Aqueous Sodium Tartrate Solutions at Various Temperatures

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Refractive index, viscosity, density, and speed of sound of solutions of sodium tartrate at (25, 35, and 45) °C have been measured. The obtained refractive index, viscosity, density, and speed of sound data were correlated with suitable equations. The experimental density data for sodium tartrate were used to obtain limiting apparent molal volume at each temperature from which the corresponding infinite dilution molal volume for tartrare ion was calculated. The obtained density data were also used together with the corresponding speed of sound data to determine isentropic compressibilities of the solutions, and these data were also fitted to an empirical equation.

Introduction

Tartaric ions in aqueous solutions are of a considerable significance in many biochemical and chemical processes.[1] In respect to these solutions, conductivity studies[2,3] have been carried out on some alkali metal and ammonium tartrates in the temperature range of (5 to 35) °C. Recently, vapor pressures of saturated solutions for some tartrate salts have been measured.[4,5] However, in respect to other thermodynamic or transport properties of tartrate salts, little information can be found in the literature. There are reports on the densities of aqueous solutions of potassium and sodium tartrates.[6,7] In the case of disodium tartrate, density values have been given[6] in the molality range of (0.0306 to 1.3115) mol·kg^{-1} at 25 °C. At the pressure of 0.35 MPa, a few apparent molal volumes for disodium tartrate have been reported.[8] In this work, refractive index, viscosity, density, and speed of sound of aqueous solutions of sodium tartrate are reported at (25, 35, and 45) °C. Density and speed of sound measurements were performed at the pressure 0.1 MPa from dilute up to saturation; and in order to calculate accurate limiting apparent volumes, enough data were obtained in the dilute region (concentrations less than 0.1 mol·kg^{-1}) at three temperatures. The appropriate equations were used to correlate the measured physical properties.

Experimental Section

Materials. Sodium tartrate with purity of minimum mass fraction of 0.995 was obtained from Merck. The salt was used without further purification, and double distilled deionized water was used.

Apparatus and Procedure. The solutions were prepared by mass using an analytical balance (Shimatzu, 321-34553, Shimatzu Co., Japan) with an uncertainty of $\pm 1 \times 10^{-7}$ kg. Refractive index measurements were made by using a refractometer (QUARTZ RS-232, Ceti, Belgium) with an uncertainty of ± 0.0001. The temperature of the refractometer was controlled with water from a large well-regulated water bath to within ± 0.01 °C using a thermostat (Hetotherm PF, Heto Lab Equipment, Denmark).

Viscosities of the solutions were measured with an Ostwald-type viscometer at a desired temperature using the above thermostat. It was assumed that the viscosity η was related to the time of flow, t_v, according to

$$\eta = \rho(At_v - B/t_v) \qquad (1)$$

In this relation ρ is density. The constants A and B for the viscometer were determined by calibrating with water and pure toluene at working temperatures. The viscosities of water and toluene were assumed to be 0.8904 mPa·s and 0.5559 mPa·s, respectively. The A and B values were found to be 0.020705 and 2.017890, respectively. The flow time, t_v, measurements were made with an electronic stopwatch having a precision of ± 0.01 s. Triplicate measurements of flow times were reproducible within ± 0.10 %. The uncertainty for the viscosimeter has been found to be ± 0.001 mPa·s.

Densities and speed of sounds were measured with a vibrating-tube densimeter (Antoine Parr DSA-500, Austria). By this apparatus, the working temperature can be controlled within ± 0.001 °C. The apparatus was calibrated at each temperature with double-distilled deionized water and dry air. For pure water, the values (997.046, 994.028, and 990.221) kg·m^{-3} for density and (1496.94, 1520.32, and 1536.94) m·s^{-1} for ultrasonic velocity were measured respectively at t = (25, 35, and 45) °C. The apparatus was also tested with the density of a known molality of aqueous NaCl using the data of Pitzer et al.[9] The uncertainty in the measurement of density and speed of sound was estimated to be ± 0.003 kg·m^{-3} for density and 0.1 m·s^{-1} for ultrasonic velocity.

Results and Discussion

The results of refractive index, viscosity, density, and speed of sound measurements are collected in Tables 1 to 3 at (25, 35, and 45) °C. Examination of the results given in Tables 1 to 3 reveals that for any concentration considered in this work (from dilute to near saturation) the obtained values for all of these physical properties decrease with an increase in the temperature. The exception is ultrasonic property for which an increase in temperature causes an increase in ultrasonic velocity values in the concentration and temperature ranges considered in this work.

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Table 1. Values of Refractive Index for Sodium Tartrate (1) + H_2O (2) System at Different Temperatures

	n_D		
100 w_1	t = 25 °C	t = 35 °C	t = 45 °C
0.00	1.3325	1.3313	1.3300
0.99	1.3343	1.3331	1.3318
1.92	1.3360	1.3346	1.3335
2.82	1.3373	1.3363	1.3351
3.71	1.3389	1.3378	1.3367
4.60	1.3405	1.3393	1.3381
5.47	1.3418	1.3408	1.3396
6.25	1.3432	1.3421	1.3410
7.14	1.3447	1.3435	1.3425
7.93	1.3460	1.3449	1.3439
8.72	1.3475	1.3462	1.3452
9.48	1.3486	1.3475	1.3464
10.26	1.3502	1.3488	1.3479
10.98	1.3511	1.3500	1.3490
11.69	1.3526	1.3512	1.3502
12.23	1.3535	1.3523	1.3513
13.14	1.3551	1.3537	1.3526
13.61	1.3557	1.3545	1.3536
14.37	1.3572	1.3560	1.3548
15.14	1.3584	1.3572	1.3562
15.77	1.3594	1.3582	1.3573
16.46	1.3607	1.3596	1.3587
16.97	1.3616	1.3606	1.3595
17.69	1.3630	1.3617	1.3607
18.25	1.3639	1.3627	1.3616
18.86	1.3649	1.3637	1.3627
19.41	1.3660	1.3646	1.3636
19.96	1.3668	1.3655	1.3644
20.48	1.3677	1.3664	1.3654
21.16	1.3689	1.3675	1.3666
21.67	1.3697	1.3685	1.3675
22.21	1.3707	1.3696	1.3684
22.81	1.3719	1.3707	1.3695
23.28	1.3728	1.3715	1.3703
24.30	1.3744	1.3731	1.3720
24.93	1.3755	1.3744	1.3732
25.77	1.3770	1.3759	1.3749
26.22	1.3778	1.3765	1.3757
26.81	1.3790	1.3777	1.3765
27.57	1.3802	1.3791	1.3778
28.59	1.3821	1.3809	1.3798
29.79	1.3840	1.3829	1.3819
30.85	1.3861	1.3848	1.3841

Table 2. Values of Viscosity for Sodium Tartrate (1) + H_2O (2) System at Different Temperatures

	η/(mPa·s)		
100 w_1	25 °C	35 °C	45 °C
0	0.890	0.729	0.600
1.9857	0.932	0.773	0.644
3.9915	0.995	0.824	0.683
6.0245	1.060	0.885	0.726
8.0095	1.137	0.952	0.782
9.9985	1.230	1.020	0.832
11.9998	1.321	1.098	0.894
13.9983	1.431	1.184	0.959
15.9968	1.560	1.278	1.024
17.9476	1.706	1.380	1.101
20.0662	1.891	1.519	1.215
21.9625	2.086	1.669	1.334
24.0197	2.301	1.857	1.475
25.9968	2.563	2.055	1.647
28.0563	2.897	2.305	1.846

The dependence of refractive index, n_D, of solutions to mass fractions of sodium tartrate, w_1, at a given temperature was described by the conventional equation:

$$n_D = n_D^{\,0} + a_0 w_1 \tag{2}$$

where n_D^0 is the refractive index of pure water and a_0 is a constant. The results of fitting of the experimental refractive index data to the eq 2 are given in Table 4. On the basis of obtained standard deviations, we conclude that the correlated results are in fairly good agreement with experiment.

Following Carton et al.,[10] the experimental viscosity data were correlated with the equation

$$\ln \eta = B(w_1) + C(w_1)/T \tag{3}$$

where

$$B(w_1) = b_0 + b_1 w_1 + b_2 {w_1}^2 \tag{3a}$$

and

$$C(w_1) = c_0 + c_1 w_1 + c_2 {w_1}^2 \tag{3b}$$

In the above equations, b_i and c_i are constants, which are obtained from fitting of the experimental viscosity data. The values of these constants are reported in Table 5. The obtained standard deviations of the fit for η at (25, 35, and 45) °C are respectively 0.008, 0.013, and 0.013. The maximum deviation between the experimental and calculated viscosity data in term of η is 2.6 %. These results show that eq 3 can be satisfactorily

Table 3. Densities ρ and Sound Velocities u for Sodium Tartrate (1) + H_2O (2) System at Different Temperatures

	ρ/(kg·m^{-3})			u/(m·s^{-1})		
m_1/(mol·kg^{-1})	t = 25 °C	t = 35 °C	t = 45 °C	t = 25 °C	t = 35 °C	t = 45 °C
0.0325	1001.45	998.34	994.47	1501.97	1524.83	1541.33
0.0351	1001.80	998.70	994.82	1502.34	1525.23	1541.65
0.0405	1002.51	999.40	995.52	1503.13	1525.96	1542.35
0.0552	1004.48	1001.34	997.43	1505.37	1528.05	1544.32
0.0576	1004.79	1001.64	997.72	1505.70	1528.37	1544.61
0.0673	1006.08	1002.91	998.99	1507.16	1529.72	1545.89
0.0747	1007.06	1003.87	999.92	1508.23	1530.73	1547.05
0.0814	1007.94	1004.73	1000.77	1509.92	1531.64	1547.72
0.1365	1015.14	1011.79	1007.83	1517.30	1539.24	1554.94
0.2798	1033.29	1029.68	1025.48	1537.54	1558.23	1572.86
0.4159	1049.92	1046.11	1041.78	1556.26	1575.76	1589.37
0.5661	1067.63	1063.54	1059.16	1576.43	1594.59	1607.33
0.7158	1084.68	1080.39	1075.77	1598.60	1615.29	1624.11
0.8880	1103.52	1098.96	1094.15	1618.47	1633.76	1644.03
1.0548	1121.13	1116.46	1111.35	1639.64	1653.59	1662.25
1.2106	1137.00	1132.16	1126.70	1659.03	1671.72	1679.24
1.4118	1156.69	1151.68	1146.41	1683.56	1694.53	1701.17
1.5925	1173.71	1168.58	1163.14	1705.11	1714.64	1719.83
1.7489	1187.90	1182.99	1176.91	1723.33	1731.98	1734.78
2.2027	1226.56	1221.08	1215.23	1773.97	1778.68	1779.72

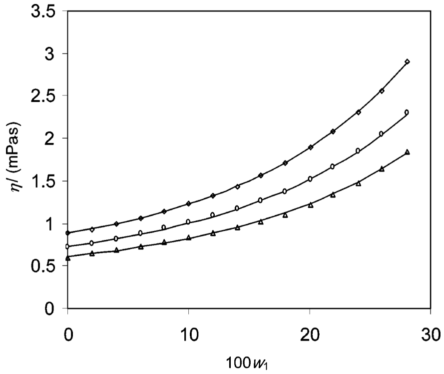

Figure 1. Viscosity of aqueous solutions of sodium tartrate (1) at different temperatures: ◇, 25 °C; ○, 35 °C; △, 45 °C; —, calculated from eq 3.

Table 4. Values of the Parameter a_0 of Equation 1 for Refractive Index of Sodium Tartrate (1) + H_2O (2) System at Different Temperatures

t/°C	$n_D{}^0$ [a]	a_0	$\sigma(n_D)$ [b]
25	1.3325	0.1731	0.0001
35	1.3313	0.1732	0.0002
45	1.3300	0.1734	0.0001

[a] These values were measured for pure water. [b] $\sigma(n_D) = [\sum_{i=1}^{N}[(n_i^{\text{cal}} - n_i^{\text{exp}})^2/N]^{0.5}]$, where N is the number of data.

Table 5. Values of the Parameters of Equation 3 for Viscosities of Sodium Tartrate (1) + H_2O (2) System at Different Temperatures

b_0	$10^4 b_1$	$10^4 b_2$	$10^3 c_0$	c_1	c_2
−6.0491	4.4785	3.0596	1.7680	7.9682	0.2498

used for correlation of our experimental viscosity data. Figure 1 shows the concentration dependence of viscosities obtained from the experiment and those generated using eq 3 with the coefficients taken from Table 5.

Apparent molal volumes in dilute region (from 0.0325 to 0.0814) mol·kg^{-1} evaluated from eq 4 can be used along with the Redlich−Mayer equation[11] (eq 5) for evaluation of the limiting apparent molal volume of sodium tartrate in water solutions, $\phi_v{}^0$ (equal to the partial molal volume at infinite dilution, $V_1{}^0$). The necessary equations have the following forms:

$$\phi_v = \left[\frac{M}{\rho} + \frac{1}{m_1}\left(\frac{1}{\rho} - \frac{1}{\rho_s}\right)\right] \tag{4}$$

$$\phi_v = \phi_v{}^0 + S_v\sqrt{m_1} + b_v m_1 \tag{5}$$

where b_v is an empirical parameter, and S_v is defined as

$$S_v = k\left[\frac{1}{2}\left(\sum_i \nu_i z_i^2\right)\right]^{3/2} \tag{6}$$

In these equations, ρ and ρ_s are density of the solution and that of pure water, respectively. ϕ_v, m_1, and M are the apparent molal volume, molality, and molar mass of electrolyte, respectively. υ_i and z_i are stoichiometric number and absolute charge of ion i, respectively. The limiting apparent molal volume of sodium tartrate in water was obtained by fitting eq 5 to the data in the dilute region. The obtained values for $V_1{}^0$ (equal to $\phi_v{}^0$) and b_v are given in Table 6. For the limiting theoretical slope, k, the values (1.868, 2.046, and 2.234) cm^3·L$^{0.5}$·mol$^{-1.5}$ given by Millero[12] were used at (25, 35, and 45) °C, respectively.

Table 6. Parameters of Equation 5 and the Values of Infinite Dilution Partial Molal Volumes of Tartrate Ion for Sodium Tartrate (1) + H_2O (2) System at Three Temperatures

t / °C	$10^6 V_1{}^0$ / m^3·mol^{-1}	$10^6 b_v$ / m^3·mol^{-2}·kg	$10^6 V_{C_4H_4O_6{}^{2-}}{}^0$ / m^3·mol^{-1}
25	57.35	15.51	59.77
35	59.76	9.71	61.44
45	61.54	6.32	62.42

Table 7. Correlation Parameters of Equation 8 and Average Relative Deviations, σ, for Aqueous Sodium Tartrate System at Different Temperatures

	A	B	C	D	σ
		t/°C = 25			
ρ/(kg·m^{-3})	1.371·10^2	−7.934	−13.366	2.529	0.01
u/(m·s^{-1})	1.582·10^2	−24.541	3.945	−1.437	0.50
β/(TPa)$^{-1}$	−155.13	19.61	35.99	−11.87	0.23
		t/°C = 35			
ρ/(kg·m^{-3})	1.355·10^2	−10.855	−8.993	1.062	0.06
u/(m·s^{-1})	1.427·10^2	−9.707	−7.353	1.598	0.46
β/(TPa)$^{-1}$	−142.23	15.80	33.60	−10.81	0.21
		t/°C = 45			
ρ/(kg·m^{-3})	1.325·10^2	−4.563	−15.821	3.442	0.08
u/(m·s^{-1})	1.427·10^2	−9.707	−7.353	1.598	0.22
β/(TPa)$^{-1}$	−136.41	22.30	24.08	−7.91	0.10

Using the additivity rule,[12] the infinite dilution partial molal volume of the tartrate ion can be calculated from the limiting apparent molal volume of sodium tartrate. According to the additivity rule, the partial molal volume of a salt at infinite dilution is the sum of infinite dilution partial molal volumes of its consisting ions, $V_1{}^0 = \sum_{i=i}^{\text{ones of the salt}} \upsilon_i V_i{}^0$, in which $V_i{}^0$ is the infinite dilution partial molal volume of ith ion. Therefore

$$V_1{}^0 = 2V_{Na^+}{}^0 + V_{C_4H_4O_6{}^{2-}} \tag{7}$$

For infinite dilution partial molal volume of sodium ion $V_{Na^+}{}^0$, Millero[12] has given the values (−1.21 × 10^{-6}, −0.30 × 10^{-6}, and 0.8 × 10^{-6}) m^3·mol^{-1} at (25, 50, and 75) °C, respectively. From fitting of these data to a straight line, the necessary values for $V_{Na^+}{}^0$ may be estimated as (−0.84 × 10^{-6} and −0.44 × 10^{-6}) m^3·mol^{-1} at 35 °C and 45 °C, respectively. The standard deviation of the fit is 0.04 × 10^{-6} m^3·mol^{-1}. Using the necessary data for $V_1{}^0$ from Table 6 and the above $V_{Na^+}{}^0$ values, the infinite dilution partial molal volume of tartrate ion, $V_{C_4H_4O_6{}^{2-}}{}^0$ can be calculated by the help of the eq 7. The results are given in Table 6. Our value, $V_1{}^0$ = 57.35 × 10^{-6} m^3·mol^{-1} at 25 °C can be compared with the corresponding values, $V_1{}^0$ = 57.87 × 10^{-6} m^3·mol^{-1} and $V_1{}^0$ = 56.87 × 10^{-6} m^3·mol^{-1} obtained respectively by Apelblat and Manzurola[6] and Patterson and Woolley,[8] and they are in good agreement. However, our $V_1{}^0$ values at 25 °C and 35 °C differ from that of Høiland and Vikingstad:[7] $V_1{}^0$ (25 °C) = 56.26 × 10^{-6} m^3·mol^{-1} and $V_1{}^0$ (35 °C) = 58.65 × 10^{-6} m^3·mol^{-1} , by 1.09 × 10^{-6} m^3·mol^{-1} and 1.11 × 10^{-6} m^3·mol^{-1} at 25 °C and 35 °C, respectivley.

The experimental density ρ and ultrasonic velocity values u given in Table 3 and the isentropic compressibility values β calculated by the help of the Laplace equation ($\beta = 1/u^2\rho$) were correlated at each working temperature with the following equation:

$$F_{sw} = F_w + Am_1 + Bm_1{}^{3/2} + Cm_1{}^2 + Dm_1{}^{5/2} \tag{8}$$

where F_{sw} is ρ, u, or β for aqueous salt solutions, and F_w is the corresponding value for the pure water. All these fittings were carried out as $\Delta F_{sw} = F_{sw} - F_w$. The results of fitting of density, ultrasonic velocity, and compressibility values for aqueous sodium tartrate solutions together with the standard deviations, σ, are presented in Table 7. Standard deviations between the calculated, F_i^{cal}, and the experimental, F_i^{exp}, values have been

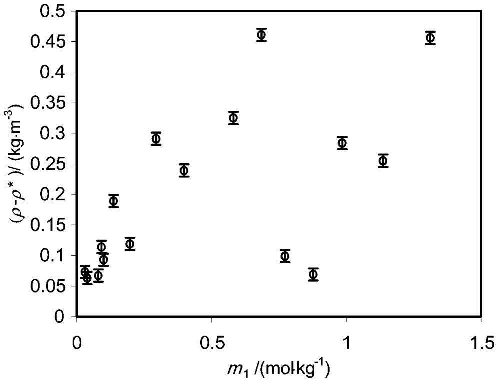

Figure 2. Density difference between Apelblat and Manzurola[6] data and this work, $\rho - \rho^*$, vs molality for aqueous sodium tartrate solutions at 25 °C.

estimated by using

$$\sigma(F) = \left[\sum_{i=1}^{N} [(F_i^{\mathrm{cal}} - F_i^{\mathrm{exp}})^2/N]^{0.5} \right] \tag{9}$$

where N is the number of experimental points. On the basis of the reported average relative deviations, we conclude that eq 8 is a suitable equation in representing the experimental ρ, u, and β values for the studied aqueous salt solutions at three temperatures.

A comparison of density data, ρ^*, reported in the literature[6,7] at 25 °C and the corresponding data, ρ, obtained using the eq 8 with the coefficients, given in the first row of Table 7 are shown in Figure 2. Figure 2 shows that there is very good agreement between our data and those reported by Apelblat and Manzurola.[6]

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